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Smart grids in China

Jiahai Yuan [*,a], Jiakun Shen [a], Li Pan [a], Changhong Zhao [a], Junjie Kang [b,**]

[a] School of Economics and Management, North China Electric Power University, China
[b] State Nuclear Power Research Institute, Beijing, China

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ABSTRACT

Smart grid is the direction of power system development and it has aroused wide attention. It is also the physical infrastructure to integrate renewable energy into the power system. In China power grid companies are the pioneer in developing smart grids. Propelled by strong demand, China has made encouraging progress in smart grid development, especially in the aspect of ultra-high voltage transmission system. However, in other aspects as distributed generation, microgrid and intelligent demand management etc., the progress is slow and limited. In this paper we analyze the policy, pilot projects, achievements and barriers of developing smart grids in China. We find that lack of a clear national strategy is one main institutional barrier. The current industrial structure of the electric power sector, or the vertical integration of power transmission with distribution and supply, is another institutional barrier. Finally we provide an outlook on smart grid development in China.

Contents

* Corresponding author. Tel.: +86 10 6177 3091.
** Corresponding author.
E-mail addresses: yuanjh126@126.com (J. Yuan), kangjunjie@snptc.com.cn (J. Kang).

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1. Introduction

Power system holds pivotal role in the renewable-based low-carbon energy system [1,2]. Smart grid is the essential platform which enables the renewable energy system. Smart grid (SG) can contribute to the renewable-based low carbon energy system in three ways. First, SG can enhance energy efficiency by improving the operation of traditional power plants and power grids. Second, SG can facilitate the integration of renewable power generation in large-scale concentrated and/or small-scale distributed ways. Third, SG can boost various novel innovations and applications in demand response and promote energy efficiency in demand side [3,4].

Since the concept of SG was proposed by EPRI in 2002, worldwide researches and construction processes of smart grids (SG) have taken off and many countries have established their own comprehensive strategies, goals and pathways to develop it [5]. In the USA, SG plan devotes to the development of safe, reliable and modern power grids, enhancement of demand-side efficiency and reduction of power supply cost under the background of aging power infrastructure. In Europe, the Super Smart Grid scheme aims at complementarily reconciling two approaches of renewable energy development, namely large-scale centralized way and small-scale, local and decentralized counterpart, to realize a transition towards a fully decarbonized electricity system. In Australia, renewable energy and energy efficiency are targeted in SG development and the focus is on intelligent meters and intelligent demand-side management. In Japan, the emphasis of SG is to build renewable-friendly power grids adapted to large-scale solar power deployment, so as to resolve the conflicts between small territory, energy resource shortage and economic development. In Korea, the emphasis of SG research is on the integration of power system with smart green cities.

SG is also being regarded seriously in China. Grid companies took the initiative in developing SG. In May of 2009, State Grid Corporation of China (SGCC) released its vision and developmental roadmap for building a Strong Smart Grid (SSG) [6]. China Southern Grid Power Corporation (CSG) proposed its vision to build a smart, high efficient and reliable green power grid in July of 2010 [7]. In November, 2009, Ministry of Science and Technology (MOST) released a special report addressing SG related technology research & development (R&D) in China [8]. Then in March of 2011in the 12th Five-year Plan (FYP) of National Economic and social Development, advancing smart grids, enhancing the resource allocation capacity of power system and improving power supply reliability, were taken as the key tasks for delivering power system transition [9], which is a clear signal that Smart Grid has been included in China's national energy policy. Shortly after that, in March of 2012, MOST issued a specialized plan for the industrialization of SG technologies and proposed to build the Chinese version of SG in 2020 [10]. In parallel to policy advancement, there are encouraging technical innovations and many pilot projects implemented by the two grid companies in China [11].

The cumulative investment in the construction of power grids accounts for roughly 36.2% of the total investment in the power sector. Though during 2001–2009 the share increased to 45%, it is still significantly below the international standard of 50–60% [12]. Presently, China (SGCC in particular) is advancing the strategy of “ultra-high voltage plus big coal power bases, big hydropower bases, big wind power bases and big nuclear power bases” with ultra-high voltage power grids consisted of 1000 kV AC and ±800 kV DC lines as the top priority. However, the inconsistency between power grid and power generation is still serious, so is the inconsistency between the backbone transmission infrastructure and local distribution networks. The major issues of the power grids in China include: regional imbalance between power resource, mostly located in northern and western China, and power demand centers, usually located in central and eastern China, with a long transmission distance ranging between 1000 and 3000 km; insufficiency in the grid-access capacity for intermittent renewable power; low automation level in distribution networks; and poor level in demand response management [12,13].

Developing SG is not simply an engineering or technical issue. Transition to smart and low carbon power systems represents multiple challenges, including institutional, economic and managerial ones. In this paper, we will first discuss the Chinese perspective of smart grid and compare the difference with those of other countries. Next we will compare the differences between smart grid and the traditional one and identity the key areas of SG development. In turn we review the policy progress relevant to SG in China. Then strategic planning on SG in China will be analyzed and progress on China's SG development will be reviewed. Next we will identify the barriers to SG development in China, in a perspective of institutional analysis. Finally we will discuss the prospective of SG in China and conclude the paper.

2. Smart grids and stakeholders in China

2.1. Perspectives on smart grid in China

SGCC is the pioneer for developing SG in China. As early as May 21 of 2009, SGCC put forwards its strategic plan for building a Strong Smart Grid (SSG). Meanwhile SGCC established an ambitious target, namely establishing digital, automated and interactive power grids which are supported by ultra-high voltage (UHV) transmission network. According to Electric Power Research Institute (EPRI) of SGCC, SG can be defined as “a new type of highly integrated power grid, which is the combination of modern advanced sensing & measurement technology, information technology, communication technology, control technology and physical power system”. SG is strong, self-healing, compatible, economical and integrative [14].

Some experts adopt the conception of “interactive power system”. A version by Chinese Academy of Science, argues that “interactive power system” is not simply the renovation of traditional power system with modern information technology [15]. According to it, the prevailing concept is unable to define the basic pattern of next generation power grid and is also unable to generalize the core of modern power system in China. Hence Wu states that “interactive grid” is not merely UHV, and it should become the primary goal of power system development in China.

Some experts define SG in other way. Yu [16] points out that the prominent feature of SG is the bi-directional flow of information and power in so as to establish a highly automated and widely distributed network for energy exchange. Also, for the purpose of real-time information exchange and nearly transient balance of demand and supply, it is necessary to introduce distributed

computation and modern communication system into the power system.

2.2. Definitions of SG around the world

In contrast to the development of UHV in China, some European countries initiated the construction of distributed grid (DG) to spread the risks. In countries like the United States and Russia, the pathway of UHV is almost abandoned. In the United States and Europe, the priority of SG development focuses on the following aspects: improving customer service, supporting the grid access of distributed renewable energy, localizing load and power supply, advanced automation and distributed intelligence, flexible grid operation, service-oriented architecture, more reliable and safe power supply, and finally energy efficiency. Specifically, the definition of Grid 2030 by the U.S. Department of Energy (DOE) goes as "a fully automated power delivery network ensuring a two-way flow of electricity and information between the power plants and appliances and all points in between"[17]. The definition by U.S. EPRI (IntelliGrid) is "one electrical power system made up of many automatic transmission and distribution systems in coordinated, effective and reliable ways to complete all of the power grid operations in such a way: self-healing and adaptive; interactive with consumers and markets; optimized to make best use of resources and equipment; predictive rather than reactive to prevent emergencies; distributed across geographical and organizational boundaries; integrated, merging monitoring, control, protection, maintenance, EMS, DMS, marketing, and IT; and more secure from attack"[18]. The definition by European Technology Forum goes as "an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies"[19].

From the above definitions, it is clear that the European viewpoint is based on the European Union's desire to standardize the power grids in member nations and to interconnect them into a European Grid, while the definitions of US DOE and EPRI are also based on the examination of American power industry and point out the future direction of development.

From different definitions of smart grid by Chinese institutions, it is clear that SGCC prefers developing UHV on the basis of existing physical infrastructure. Informatization, digitization, automation and interaction, all these are the main features of future Smart Grid, but are described as just the characteristics of UHV power grid in the definition of SGCC. As a matter of fact, "next generation Grid technology", instead of smart grid is used in its definition. In a sense, SG is deliberately ignored. Perhaps the concept of "interactive grid" is more accurate and consistent with the global consensus on the future of power system.

Table 1
Stakeholders and their concerns on SG.
Source: [20–21].

Stakeholders	Major concerns
Central government	Solution for the economy-energy-environment puzzle Deployment of renewable energy Revitalization of equipment manufacturing industry and creation of strategic new industry
Local government	Adequacy for local power supply Promoting the development of local economy
Equipment manufacturers	Establishing the technology standard as soon as possible Seizing market share
Grid companies	Integrating renewable energy into the grids Pricing mechanism and cost recovery Real-time information of customer demand
Power consumer	Stable power supply Cost efficient of power supply
R&D institution	Holding advantageous position in setting up the world industry standards
Peripheral industries (ICT, electric vehicle, etc.)	Promoting the integration of multi-network Promoting the innovation and deployment of new technologies in power grids Supporting the development of EV industry

2.3. Stakeholders of SG

For a grid company who desires to strengthen its vertical integration in the power system, SGCC naturally tends to take UHV as its priority. The concept of "interactive power grid" is proposed for the purpose of seizing advantage on the standard of SG for China in global arena [15], while [16] emphasizes the importance of real-time information in process of the smart grid operation from the perspective of practical work. As SG covers a wide variety of functions and applications, different stakeholders have different concerns on its development (Table 1).

3. Comparison of traditional and smart grid

Though smart grid is defined differently around the world, it is clear that there exists vast difference between it and the traditional power system. Generally speaking, SG is efficient, reliable, interactive and compatibly open. In Table 2 their differences are compared in terms of efficiency, reliability, compatibility, interaction and openness.

Table 2
Comparison of smart grid and traditional grid.
Source: [22].

Feature	Traditional grid	Smart grid
Efficiency	The integration of operational data and asset management is bad.	*Efficient operation*: expand data acquisition and pay close attention to accident prevention to reduce negative impact on customers and improve operational efficiency. *Asset optimization*: introduce advanced information and monitoring technology to optimize the usage of resources and equipment, lower operation and maintenance costs.
Reliability	The ability of self-healing is poor and it cannot cope with the natural disasters well.	*Self-healing*: continuous assessment can detect, analyze, respond to and even restore power equipments or abnormal operation in local networks. *Security*: effectively resist the damages of external attacks from both physical system or computer systems.
Compatibility	It is designed mainly for concentrated power generation and is not adapted to distributed energy.	A large number of distributed renewable energy sources can be easily accessed to the grid.
Openness	Enforce strict admittance to equipments.	Allow free access to the grid and interaction between equipments and the grid.
Interactivity	It is unilateral and customers have to accept whatever the service.	Inform customers and encourage users to participate in power market. Customer is no longer a passive user and has power to choose among service providers.

Table 3
Key aspects of developing smart grids in China.
Source: [23].

Aspect	Requirements	Key technologies
Generation	Raise safe operation of power system by a substantial magnitude Promote large-scale deployment of renewable energy Promote R&D on utility-scale energy storage technology to adapt to the rapid development of intermittent power supply	• Coordination technology between the grid and the regular plants • Integration and control technology for renewable energy • Large-capacity energy storage technology
Transmission	Improve the transmission capacity greatly and reduce transmission cost Optimize the operating conditions of transmission network Improve the stability level of power system and promote system interconnection Realize condition assessment, fault diagnosis and online status maintenance and risk early warning	• GPS positioning, advanced intelligent detection and inspection technology • Intelligent diagnostic analysis and decision technology • Condition based maintenance, life-cycle equipment management and intelligent disaster prevention technology
Transformation	Improve system stability and reliability, transmission capacity, as well as the health level Provide information for smart dispatch of power system Enhance the level of substation assets management and operation	• Intelligent substation automation technology • Integration of online testing and intelligent diagnosis • Intelligent detection device and automatic verification device
Distribution	Enhance the reliability of power supply, system efficiency and terminal power quality Realize distributed generation, energy storage and micro network interconnection Coordinate operation optimization, efficient interaction of demand side management, and realize integration management of distribution assets	• Power distribution automation system and integrated intelligent distribution network control technology • Distribution dispatch and information system • Distributed generation/storage and micro network access and coordinated control technology
Utilization	Enhance the quality of power supply service Improve terminal energy efficiency and grid operation efficiency Raise the proportion of clean energy in terminal energy consumption Promote energy conservation and emissions reduction	• Real-time data-mining and management of customer consumption patterns and behaviors • Intelligent community/buildings • intelligent customer service system • Customer-side distributed power and energy storage system
Dispatching	Realize networked data transmission and visualization of operation monitoring Realize dynamic safety assessment and refined dispatch Realize automatic operation control and optimized generation-grid coordination	• Energy management system • wide area measurement system (WAMS) • Dynamic stability test and early warning system • Schedule management system
Information platform	Realize whole process information integration Realize resource optimization and risk management on grid level Improve interactions among grid operator and key stakeholders Realize smart decision in big data system Provide communication carriers for Internet of Things (IOT) and expand its applications	• Modern information technology • Big data platform for the whole process of power supply chain • Integrated communication platform • Business collaboration and interoperability platform

Technology advance must be realized in different aspects of power generation, transmission, substation, power distribution and utilization etc., in order to transform the theoretical difference into reality (Table 3).

4. Policy progress relevant to smart grid in China

The Ministry of Science and Technology (MOST) formulated a special plan for key SG technology industrialization projects during the 12th Five-Year-Plan in 2012 [10]. According to the plan, SG will step into the overall construction in a few years. Ever since 2006, a series of policies, including *renewable energy law*, *pilot management scheme for renewable energy pricing and cost sharing, special fund for renewable energy development* (*interim measures*) have been issued and provide strong support for renewable energy development in China. Meanwhile, they also promote the development of SG in China. Whatever, in national level no specific strategy or policy has been designed for SG.

SG is an extremely complex system, including generation, transmission, substation, distribution, consumption, power dispatch, and information platform. All policies in these areas are also related to SG. We therefore summarize the related policies in a chronicle way (Table 4). It is evident that China Government has provided comprehensive incentives for developing SG, covering key equipments manufacturing, grid-access technology for power plants, and deployment of renewable energy in the power systems. Particularly, in the 12th Five-year-plan for National Economy and social Development (FYP), SG is taken as the key area of industrial upgrading and strategic emerging manufacturing industry, the key area of reform in the energy production and consumption system, the critical means for green development and positive climate change response, and the priority for national science and technology development [43].

In addition, the trend that SG will integrate with the Internet of Things (IOT) is also becoming increasingly apparent, along with the development of IOT. It can be easily reasoned that the government prefers to support the development of new energy and equipment manufacturing industry. The main purpose is to promote the economy development. While for the power system, on national level no clear direction has yet been pointed out for it. All the related policies issued in recent years are concerned with solving the issues of deploying renewable energy and energy conservation in the current power system, but are not for the future development of SG. Lack of clear national strategy and integrative policy is the leading obstacle.

5. Strategic planning on smart grid in China

Unlike in other countries where government plays a leading role in the development of SG, in China grid companies have more

Table 4
Policies relevant to smart grid development in China.
Source: [24–42].

Time issued	Policy	Main content	Relation with SG
January 2006	Renewable energy pricing and cost-sharing (pilot management scheme) [24]	*Stipulate two kinds of pricing mechanisms*: government direct pricing and government guidance pricing. The guidance prices will be determined based on franchise bidding. The difference between RE price and regional de-sulfurized coal power will be shared among all customers.	Related with the price of renewable energy connected to power grids.
May 2006	Special fund for renewable energy development in buildings (interim measure) [25]	Central government will allocate special fund to support renewable energy development in buildings.	Related with the deployment of new energy in SG.
November 2006	Management measures on auxiliary service in power system [26]	*Stipulate that power plants will provide two kinds of ancillary services*: basic and paid ancillary services. It also indicates the provision and invocation, measurement and assessment, compensation and supervision related with auxiliary service.	Related with grid-connection of renewable energy in SG.
August 2007	Energy-saving power generation dispatching (trial) [27]	Stipulate energy saving as the principle of dispatch. Put renewable energy on the priority position in the schedule plan. Optimize dispatch in provincial and regional levels to minimize energy consumption and pollutant emissions.	Scheduling aspect of SG.
October 2007	Admittance management rules on new energy vehicles [28]	Provide preferential measures for the production of EV, including management way, production resources, technology and others.	Associated of EV/new energy storage applications in SG.
August 2008	Special fund for wind power equipment industry (interim measures) [29]	Provide manufacturers with Subsidies for the first 50wind turbines (verified new model). The subsidy can only be used for R&D activity.	Related with new energy equipment manufacturing/renewable energy deployment in SG.
January 2009	Demonstration and commercialization financial subsidy fund for energy-saving and new energy vehicle (trial) [30]	Encourage usage of EV in public service in selected 13 cities. Provide subsidy for EV customers.	Associated with EV/new energy storage applications in SG.
March 2009	Finical aid fund for solar energy applications in buildings (trial) [31]	Provide subsidy to solar power generation in buildings and the subsidy will be subject to adjustment according to technology progress.	Related with the deployment of distributed energy in SG.
May 2009	Equipment manufacturing industry restructuring and revitalization plan [32]	Declare objective including GW-scale nuclear power unit, new energy power generation equipment and others to achieve independent manufacturing.	Related with new energy equipment manufacturing connected to the SG.
July 2009	Golden sun demonstration project [33]	Arrange fund from renewable energy fund to support PV applications.	Related with new energy equipment manufacturing connected to the SG and distributed energy in SG.
July 2009	Reform of wind power pricing mechanism [34]	Set benchmarking price for wind power into four resource areas.	Related with renewable energy connect to the SG and pricing mechanism.
April 2010	Renewable energy law (amendment) [35]	Stipulate full protective purchase of renewable generation.	Related with renewable energy distributed generation and grid connection to the SG.
September 2010	Fund management rules for clean development mechanism in China [36]	Establish national CDM fund as a response to climate change.	Related with new energy applications.
August 2011	Reform on PV pricing mechanism [37]	Stipulate direct government price for PV power generation.	Related with distributed energy in SG and pricing mechanism.
November 2011	Instruction on implementing ladder pricing mechanism in resident customers [38]	Reduce cross-subsidy and encourage energy conservation in resident power consumption.	Related with pricing mechanism in SG.
July 2012	Pilot project management for demand-side management in cities [39]	Provide subsidy to cities for implementing DSM	Associated with customer response in SG.
December 2012	Management rules on the special fund for strategic emerging industry (trial) [40]	Establish special fund for promoting the development of strategic emerging industry.	Associated with the SG industry development funds.
July 2013	Financial subsidy for distributed PV project [41]	Subsidy for distributed PV based on resource conditions	Related with distributed energy in SG.
September 2013	Promotion and application of electric vehicles [42]	Establish special fund to provide subsidy for electric vehicles and charging facilities.	Related with new energy applications.

important role. There are only two grid companies in China: SGCC and CSG. These two companies take charge of almost all power transmission, distribution, dispatch, and customers service activities in China. The SGCC is a backbone state-owned enterprise covering 26 provinces, municipalities and autonomous regions, while the CSG serves other five provinces in the south, including Guangdong, Guangxi, Hainan, Yunnan, and Guizhou. As they serve different regions, they do not need to compete with each other.

5.1. Grid companies

5.1.1. SGCC

As the largest grid operator in China, SGCC is the main promoter and developer of smart grid applications in China. SGCC launched a comprehensive planning for smart grid in 2010. According to the planning, Strong Smart Grid, which is backboned by UHV and coordinates the development of power grids at all level, will be the development direction of SGCC. A three-stage detailed plan is formulated to guide the development [23].

The emphasis of the first stage (2009–2010) is R&D on technical innovation and pilot projects. Now, the task of the first stage has been accomplished, with a plan, two fundamental construction programs, 21 demonstration projects, and 10 specific research projects finished. In the second stage (2011–2015), smart grids in China should be largely promoted. Specifically, the construction of UHVDC and power distribution network would be accelerated. During the stage, the technical standard system for SG should be established and perfected. Also, major advance should be made on key technologies and equipments and they would be widely used in practice. In the last stage (2016–2020), the resource distribution

ability, stability, interactivity between the power grid and the consumer should be enhanced, and a strong smart gird will be finally built. It is expected by the plan that at that time the integration of clean energy and its coordinative control should be significantly improved and utility-scale energy storage should be widely used. 100 GW wind power and 20 GW solar power should be connected to national power system and the system should be able to optimize more than 400 GW generation resource. The operation efficiency of the power system should also be improved significantly and the line loss would be lowered to 5.8% in 2020. Meanwhile, EV supporting and smart building infrastructure should be established and various novel value-added services would emerge. At that time various new business models around power grids would be established and widely accepted, thus creating a huge market.

5.1.2. CSG

Another power grid operator, CSG, has also put forward its overall objectives and principles concerning smart grid development [44]. CSG proposed to create a smart, efficient and reliable green grid, to promote resource-conservation and build an environment-friendly society.

A two-stage planning is proposed by CSG for the development of SG. The first stage (2010–2013) is planning, research and demonstration. To solve the problems in generation, transmission, substation, distribution, consumption, and dispatching, CSG would focus on R&D of key technologies and actively participate in the Key Technology R&D program initiated by MOST. The second stage (2012 and after) is the stage of demonstration and application.

5.2. NDRC

As the most powerful ministry in China, NDRC plays essential role in the development of any industries by formulating industrial planning, approving investment projects and providing fiscal support. In 2012 NDRC issued a special plan for "the industrialization of Smart Grid key science and technology" [45]. The plan stipulates the overall objective of developing SG in China as (1) acquisition of key technologies such as large-scale access of renewable energy, energy storage, and smart distribution, etc.; (2) formulation independent technology system and standard system for SG and establishment of an integrated supply chain; and (3) and finally completion of the construction of modern smart grids in China. The plan also proposes to deploy demonstration projects and industrial training to realize the targets, including 20–30 projects for component technologies, 3–5 comprehensive projects, 5–10 Smart City projects, and 50 smart park projects. It is worth noting the demonstration projects are provided by two grid companies and in this point, the NDRC plan intersects with the company-level plans.

5.3. Brief comments

From the review on the relevant plans, we can have some interesting observations. On ministry level, the interest of NDRC is focused on the manufacturing industry and independent intellectual property rights. While for SGCC, UHV-based smart grid is the priority and SGCC hopes to take the leadership in China's SG development. Therefore, SGCC formulates a very comprehensive and detailed plan for it. CSG, as a late comer, pays more attention on the development of relevant technologies and has a close eye the worldwide progress, but before the issue of explicit national policy will not arrange specific plan for it. It is also worth noting that even though manufacturing industries, renewable energy developers, EV industry and terminal customers are important stakeholders of smart grid, their concerns can hardly be expressed in the existing plans.

6. Progress of smart grid development in China

6.1. Generation

In recent years, there is a rapid growth in China's power generation capacity and a significant improvement in the technology level of the power generation equipment. Clean energy generation develops rapidly and China becomes the largest wind power developer in the world. But thermal power, especially coal power still holds the leading position in the generation mix. So there is still a long way for China to diversify its generation mix and cut reliance on fossil power. Also, due to the geographical conditions and natural resources restrictions, the installation of hydropower, pumped storage, gas and others power sources which can follow the demand quickly and provide auxiliary services to the power system, is insufficient and largely hinders the large-scale integration of renewable energy. Table 5 provides information on progress in generation sector, including coordination technology for conventional power plant and power grid, connection, control and operation technology for renewable power generation, energy storage, and capacity building for the large-scale integration of wind and solar power. It is evident that China has established national test center for wind and solar power and made smooth progress on the development of 10 large-scale wind power bases. Relevant technical standards for the coordination between power plants and power grids are improving. The establishment of technical standards for grid-access, control and

Table 5
Progress in generation sector.

Key aspect	Project deployment and progress
Large scale integration of wind power	Formulate plan for developing 10 large-scale wind power bases (ranging between 3 and 10 GW) and the plan has come into effect.
Key technologies for the coordination of conventional power plant and power grid	Formulate a series of national technical conditions and test standards for the coordination between power grids and plants.
Grid connection, control and operation technologies for renewable energy power generation	In the end of 2011, the first pilot project on distributed generation, energy storage and micro-grid was accepted by SGCC and put into operation.
National wind power and solar power research and test center	On January of 2011, the National Research and Test Center for wind power was put into operation by ERI, SGCC. On July of 2012, the National Research and Test Center for solar power was put into operation by ERI, SGCC.
National demonstration project of wind/solar energy storage project	On December of 2012, first demonstration energy-storage project was put into operation by BYD corporation.
R&D and application of large-capacity energy storage equipment	Large-scale energy storage system is listed as one of the nine key major technologies in smart grid industrialization projects by MOST but no breakthrough has been made yet. Pumped storage hydropower station is taken as the priority presently.

Table 6
Progress in transmission sector.

Key aspect	Project deployment and progress
FACTS application	By 2012, SVC, FSC, TCSC, CSR and STATCOM devices have been successfully used in practical projects. Presently the R&D direction focuses on fault current limiter (FCL) and other advanced equipments.
Flexible HVDC	In July of 2011, the first flexible HVDC transmission project in Asia was commissioned in Shanghai.
Intelligent inspection of power transmission lines	Intelligent GPS patrol and helicopter patrol have been tested and proved the feasibility. The first set of unmanned helicopter patrol equipment has been made by SGCC in China. Various patrol robots have been developed by Chinese Academy of science (CAS), Wuhan university and other institutions.
Transmission line condition assessment and maintenance technology	The safety assessment on the components of transmission system and the corridor has been completed. Condition based maintenance is now widely implemented in China.

Table 7
Progress in transformation sector.

Key aspect	Project deployment and progress
Construction and renovation of smart substation	SGCC has already completed the renovation of 1000 substations, and plans to build another 5100 smart substations and renovate 1000 substations during the 12th FYP period.
Intelligent substation operations	Reengineer the production process for smart substation and introduce the standardized mode of “dispatch & control center plus operation station” in most of the power supply companies.

Table 8
Progress in distribution sector.

Key aspect	Project deployment and progress
Distribution automation Integrated support system for distribution network control	In major cities the structure of distribution network is approaching mature. The primary equipments that can satisfy the requirement of distribution automation are technically mature. The terminal devices of distribution automation are technically mature. Various communication and host station systems are gradually applied in practical projects.
Construction of distribution information system	Intelligent decision support system for distribution network planning is in the process of comprehensive popularization.
Integration and control of distributed generation, energy storage and micro-grid	Pilot projects on distributed generation and energy storage have been implemented. Some customer-side roof PV projects have been put into operation. On technical level, currently the R&D activities mainly focus on the optimization, modeling and simulation of micro-grid and distributed generation.

operation of renewable energy are also in process. Pilot project for distributed generation, energy storage and micro-grid has been implemented but the breakthrough on large-capacity energy storage is yet to be made.

6.2. Transmission

SGCC has comprehensively grasped the core technologies of UHV transmission system and developed the cutting-edge AC (1000 kV) and DC ($\pm$800 kV) UHV equipments as well as the test system, which effectively improve the safety and transmission capacity of the power grid. Table 6 provides information on the overall progress in transmission aspect. It is evident that China has made remarkable progress on FACTS and flexible HVDC technology R&D and application, and grid companies have already achieved the practical engineering progress on these technologies and integrated them into their operation practices. The UHV transmission technology is already growing mature in China with integral set of technical standards system. The multi-terminal flexible HVDC technology for accessing renewable energy into the power grids is making progress quickly. However, the coordinated planning and development between renewable energy (especially wind power) and power grid is still problematic and partly results in serious curtailment of wind power in north China. The underlying factors include policy emphasis on capacity rather than utilization, coordination issues between central and local governments, and among different government agencies, and lack of clear national technical codes for grid-access [46,47].

6.3. Transformation

Renovation of power system, condition based maintenance, and comprehensive automation for substation have been widely implemented in China. Now China is the leader in field of substation automation and has realized domestic manufacturing of the key equipments with proprietary intellectual property rights. All the newly constructed substations in China are equipped with integrated automation system and most of the existing substations have been upgraded. In all the substations of 110 kV and above, function of “four-remote”, viz., remote-metering, remote-signaling, remote-control and remote-regulation has been applied. Also, China has made substantial progress in reengineering the business process to adapt to the improvement in transformation technology (Table 7). The priority in this section is the automation of transformer substations, and China has already completed the localization of the second version IEC 61850 and updated most of its 220 kV and above substations.

6.4. Distribution

Automation technology for power distribution has been deeply researched and preliminarily applied in the power system in China. Integration of distributed renewable generation on the distribution network is researched with remarkable results. In part of cities, various systems, including geographic information system (GIS), production management system (PMS), fault management system (FMS) and work management system (WMS), and implemented with the distribution monitoring system (DSCADA),

Table 9
Progress in utilization sector.

Key aspect	Project deployment and progress
Customer information collection system	The system is undergoing comprehensive construction in urban regions in both SGCC and CSG. In the future, it will be applied in rural regions.
Smart building/community	Application of intelligent building has been initiated in Beijing, Shanghai and other cities. SGCC has deployed a pilot smart community project (Sino-Singapore Smart Eco-city) in Tianjin.
Charging infrastructure for EV	*SGCC*: In 2009, the first charging station was developed in Shanghai and in 2010 the first operational station was put into operation in Nanjing. *CSG*: In 2010, two charging stations with a total of 134 charging piles were put into operation in Shenzhen. By 2011, 310 charging stations with a total of 16.184 charging piles had been developed in China and covered 80% of provinces. Shanghai municipal government has issued subsidy policy to encourage private investment in charging stations and promises to underwrite 30% of the investment.
Research and test center for smart power utilization	The center has been set up by EPRI of SGCC in 2012.

Table 10
Progress in dispatch sector.

Key aspect	Project deployment and progress
Communication network project	It is setting up fiber-optic network, to further improve the performance of information network, safety and reliability, etc.
Access network for low-voltage power system	100% Fiber-optic network coverage is under construction in newly-constructed urban communities. And tri-networks integration is under the way.
ERP project	SGCC and CSG have completed the construction of enterprise resource planning system in 2012.
Integration of information applications	The projects include whole-process energy management system, life-cycle asset management system, customer relationship management (CRM) and enterprise risk management system and are under way.

customer management system (CMS), and enterprise resource planning (ERP) system have been developed and put into operation. In a word, the public supporting platform for handling distribution business has formed. However, the overall power supply capacity of distribution network and its reliability is still poor. Distribution automation has just covered about 9% of the distribution system and is often at idle state. Communication information network on distribution side is still in the early development stage. The applications of energy saving technology in distribution network are limited. The R&D and applications on distributed system and micro-grid is also insufficient. Table 8 presents an overview on the progress in distribution sector. The priority in this section is advanced automation in distribution system operation and its management, as well as the supporting technologies. Many institutions or companies are conducting R&D on it, while some power supply enterprises also begin engineering demonstrations at different scales. The other priority is distributed generation and micro-grid, but it is still far from maturity.

6.5. Utilization

Both SGCC and CSG have standardized their customer service system and business process in a practical way. Research on information collection system for power customers is widely implemented and in part SGCC regions concentrated metering system is experimented. In CSG, metering automation system is been implemented with effort. Demand side management (DSM) has been widely deployed and receives considerable effect on energy conservation. Related standards, regulations and rules have been developed for information-based marketing support and customer service systems. Research on the key technologies for charging electric vehicles has been initiated and some charging stations have been established in metropolis as Beijing and Shanghai for research and test purpose. However, the intelligent two-way interactive service platform has yet to be established. The technical support system for customer information collection and intelligent energy service is yet to be developed. Key technologies and applications for smart community, smart building, and customer-side distributed generation and energy storage are still in the void. Detection and management on smart metering devices is yet to be deployed. More importantly, the relevant standard system for smart power utilization is yet to be formulated. Table 9 presents an overview on the progress in this aspect. It is evident that the deployment of smart meters is moving forward quickly; the demonstration of smart building and smart community is initiated. For integrating of electric vehicles, the key barrier is charging infrastructure.

6.6. Dispatch

SGCC has occupied international advanced level on the technology and equipment of dispatch system and has technical advantages in perspectives of protective relaying, safety automation, WAMS, on-line stability analysis and early warning, secondary system safety protection. While CSG has just developed its automation system for dispatch in recent years and has limited experience on it. But in the past years, SCADA/EMS is widely applied in the CSG and contributed to the improvement on dispatch automation. But for both SGCC and CSG, the technology development on power system dispatch lags behind the development of UHV and large-scale renewable energy base. For example, the technology of on-line power system safety analysis and control is weak. The prediction and regulation capability for the output of intermittent resources as large-scale wind power and solar power is also weak. In perspective of energy-saving dispatch, there is also much space to be improved. Table 10 presents an overview on the progress in this sector.

6.7. Comprehensive projects

Besides the development of these special projects, some comprehensive demonstration projects have been deployed in China, for example, the Sino-Singapore Eco-City Smart Grid Demonstration Project and the Shanghai Expo Demonstration Project.

The 2010 Shanghai Expo project is the first comprehensive demonstration project in China. The purpose of the project is to

provide a window to the public on what smart grid can do for them. Also, it provide an opportunity for SGCC (and Chinese Government as well) to show its (China's) technical capability on power engineering to the global society. It includes 9 demonstration projects and 4 presentation projects. Demonstration projects includes applications such as intelligent substation, distribution automation, fault repair management systems, power quality monitoring, information collection system, energy storage systems, new energy access, smart building/home, and EV charging and discharging. The presentation projects include smart dispatch, smart transmission, information platform and visualization.

While the Shanghai Expo project is mainly for presentation purpose, the Sino-Singapore Eco-City project is for practical application and serves as a prototype on the future smart grid services in cities. It covers almost all the aspects of applications: intelligent generation with energy storage and distribute source, standardized and safe intelligent transmission with digitization line, intelligent Substation with digital information, networked communication platform, standardized information sharing, and advanced interactive applications, intelligent distribution based on distribution automation and featured with self-healing, flexible and adjustable, two-way interactive service platform including information collection system, intelligent two-way interactive services platform, intelligent power utilization based on smart community/buildings and charging facilities, high-speed communication and information network, and visualization platform integrated with GPS and analysis functions.

7. Institutional barriers and policy implications

Transition to a smart and low carbon power system represents multiple institutional challenges. For one thing, renewable energy in different forms is distributed and intermittent in nature. For another thing, without technically feasible energy storage options, power system must be balanced in real-time. Therefore, historically operators of the "dumb grid" were primarily concerned with stable and reliable operation of the system. The grid was operated using a combination of command-and-control actions and hierarchical decision-making. Perhaps most importantly, the preferences of customers were largely left out of the planning and operations process in traditional power grids.

Integration of medium-and-small-scale renewable generation will face huge challenge. As discussed above, smart grid based on renewable generation and energy storage technologies radically differs with traditional one. In China, renewable generation as wind and solar power is integrated into the system by building large-scale bases and then constructing transmission system to deliver it. In this way, wind farms are taken as bulk generation of coal-based units. However the integration of medium-and-small scale renewables into the grid means that they will be connected in the distribution system or directly built on customers' houses/buildings. So first of all, level playground for small and private investors is needed to attract millions of prospective individuals into the power sector. Then regarding power grid as public-accessible public goods and ensuring fair grid-access is another priority to overcome this barrier.

Pricing mechanism poses the biggest challenge to smart customer management. Though currently smart meter and the related information and management technologies are the focus of R&D and pilot projects, reform in price mechanism plays the critical role. First of all, retail tariff must reflect the cost of energy service in consideration of the time served and quality requirement. Secondly, currently there is only wholesale generation price and final consumption tariff based on customer classification, while grid companies' revenue is the difference between them multiplying by power supply to different customers. Under this situation, Grid companies have no incentive to deliver demand side management. Meanwhile, in China price policy has historically assumed economic growth and social stability functions in China. Therefore, pricing reform can be regarded as a touchstone to see whether Chinese Government is serious to power sector deregulation.

The integration of medium-and-small scale renewable generation as well as the pricing mechanism reform also calls for the gradual redefinition of the power grids and restructuring of the utility companies. It would pose the most difficult institutional puzzle for developing smart grid in China. Currently, SGCC, the biggest national grid company is the first mover of smart grid. But the focus of SGCC is on UHV and long-distant transmission system, which can serve as a physical infrastructure to maintain and strengthen its vertical monopoly power. However, the worldwide trend requires splitting the grid company into transmission operator, distribution operator and retailers, among which transmission and distribution operator will provide public goods to generators, retailers and customers. Without clear-cut separation of public goods and private goods, it is unlikely that smart grid can function as expected. The puzzle is that, the grid company would have no incentive to develop SG if it was destined to be dismantled. Therefore, a subtle design to synchronize the SG roadmap with power sector deregulation is necessary.

Finally, there is another challenge to draft a clear national strategy and roadmap for developing SSG when trying to put all the elaborated components together and into operation. Smart grid is perhaps the most complicated manmade system and involves at least electric equipment manufacturing industry, power industry, information and communication industry and other novel industries which provide component solutions. Some components, as smart substation, FACTS, HVDC, Wide-area monitoring and control technology are mature and available. Others, like smart meters, DG, micro-grid, next generation communication and control system, Internet of Things, are still in R&D or early pilot stage. Therefore, drafting a clear national strategy and roadmap based on comprehensive appraisals of numerous component technologies and their launch pathways poses another puzzle for developing SG in China. An accompanied issue is how to integrate the international endeavors with domestic efforts.

8. Prospective of smart grid in China

8.1. Investment on SG in China, 2011–2020

China's rapid economic growth is accompanied by swift growth of electricity consumption. It is projected that in 2015 total electricity demand will reach 5815 TWh and the maximum load will reach 1300 GW; in 2020 total electricity demand will reach 7800 TWh and the maximum load will reach 1790 GW [3]. Accordingly, based on the planning of SGCC and CSG, We compile the estimated investment on power in China during 2011–2020 in Table 11 [6,23].

Table 11
Estimated investment on power grid in China, 2011–2020 (unit: billion RMB).

	2006–10	2011–15	2016–20
SGCC	1215	1500	1400
CSG	234	288	270
Total	1449	1788	1670

Note: 1 US$=6.3 RMB in 2012.
Note: The data for SGCC is sourced from [6] and the data for CSG is from [23].

Table 12
Estimated investment on smart grid in China, 2011–2020 (unit: billion RMB).

	2011–15	2016–20
Total power grid investment	1788	1670
Share of SG in total power grid investment	11.7%	12.5%
Total SG investment	209.2	208.7
Generation	3.35	3.34
Transmission	10.87	12.94
Smart substation	43.72	40.70
Distribution	45.4	48.4
Utilization	69.24	64.28
Dispatch	7.32	7.93
Information and communication	29.30	31.10

Note: The total power investment is sourced from [23], while the investment for SG and its compositions are estimated based upon current investment share. Hence the estimate may be inaccurate when the focus of SG development changes in the future.

According to the planning rate for investment in smart grid over total power grid investment and the detailed investment share, we compile China's SG investment into 2020 in Table 12. We find that about 25% of SG investment is on transmission and substation, 23% is on distribution, 30% is on customer side and another 18% is on dispatch information and communication.

8.2. Benefits of developing SG in China

With the expected development, SG will result in massive benefits. From a utility's perspective, a Smart Grid can be viewed as a means to further five primary goals: (1) enhance customer service; (2) improve operational efficiency; (3) enhance demand response and load control; (4) transform customer energy use behavior; and (5) support more utility energy efficiency investment [21,48]. From the perspective of the government or the whole society, developing smart grid can bring forth more energy conservation and GHG reduction than would otherwise be attainable, and promote employment and economic growth. In this subsection, the benefits of developing SG in China will be quantified in six aspects, viz., avoiding investment in power sector, reducing the operation cost of power system, resulting environmental benefits, bringing forth customer value added, promoting related industrial growth, and finally promoting employment and stimulating economic development.

Start with avoided investment in power sector. It is estimated that in 2020 the deployment of SG would effectively avoid 63 GW of coal power installation, or reduction investment in coal power plant of 220 billion RMB, which in turn would avoid annual fuel cost of 19 billion RMB. Assuming that the investment rate between power generation and grid is 1:1.5, the avoided investment in power grid would amount to 330 billion RMB. For system operation, SG could promote efficiency improvement of the traditional thermal power plants and decrease coal consumption per kWh electricity generation by 5.8 g, which would amount to annual energy conservation of 32 million tonnes coal equivalent (Mtce). For line loss, it is estimated that SG could reduce overall line loss of the power system by one percent point, which would amount to annual energy conservation of 25 Mtce in 2020. Turn to clean development. It is estimated that development of SG would increase renewable energy (wind and solar power) installation at least by 25–30 GW in 2020, which could substitute 45 Mtce of primary energy consumption annually. SG can also promote the development of electric vehicles (EV). According to the industry data, EV will emit 12 CO_2 kg per 100 km mileage, while a regular car will emit 19 kg per 100 km mileage. So it is evident that for the same 100 km mileage, EV can reduce CO_2 emissions by 7 kg. Suppose that in 2020 there would be a total of 30 million EVs in China, with an annual mileage of 10,000 km, the penetration of EV supported by smart grid could reduce CO_2 emissions by 21 Mt [23,44].

SG can bring forth vast benefits to customers in term of reduced electricity bill. According to the estimate by SGCC and CSG, SG could bring forth a total of 4850 TWh electricity conservation in China during 2011–2020, which could amount to saving of 2790 billion RMB for customers [23,44].

SG will also promote the development of related industries. Besides renewable sectors like wind turbine and PV panel manufacturing, sectors like EV manufacturing, ICT industry, smart appliances and smart meters etc will benefit from the development of smart grid. Though it is difficult to quantify the economic value, it is certainly that SG will promote the restructuring of Chinese economy and contribute to millions of employment in these hi-tech industries.

9. Conclusion

China has made encouraging progress in smart grid development, especially in the aspect of ultra-high voltage transmission system. However, in other aspects like distributed generation, micro-grid and intelligent demand management, the progress is slow and limited. Our review reveals lack of a clear national strategy and roadmap, as well as the grid companies' monopoly position and their incentive structure under the existing regulation environment are the main underlying factors contributing to the imbalanced development of smart grid in China. China must prudently promote power sector reform along with the development of smart grid. In this way SG will have a bright future and contribute greatly to renewable energy development and energy conservation in China.

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